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PAPER #14

THE USE OF ACOUSTIC EMISSION FOR DETECTION OF ACTIVE CORROSION AND DEGRADED ADHESIVE BONDING IN AIRCRAFT STRUCTURE

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ABSTRACT

Procedures have been developed by engineers at Sacramento Air Logistics Center to detect active corrosion in aluminum structure and moisture-degraded adhesive bonding in composite honeycomb using acoustic emission monitoring. Simple heating methods employing a hot air gun or heat lamp are used to increase emissions from active corrosion sources, and to create the stresses necessary to break moisture-degraded adhesive bonds. Corrosion detection in aluminum skin and honeycomb core has proven very successful. Detection of moisture-degraded bonding between aluminum skin and phenolic core on the F-111 vertical stabilizer leading edge has been substantially improved and simplified. Acoustic emission is replacing X-ray and ultrasonic inspection procedures in these applications, with direct benefits realized in a 75% reduction of inspection time and costs, fewer work flow interruptions, and better defect area definition.

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Introduction

The problem of water intrusion into bonded honeycomb panels on the F-111 aircraft has generated a need for inspection methods more sensitive and specific than the X-ray, eddysonic, and ultrasonic methods heretofore applied. In May 1974 the Materials and Test Branch of Sacramento Air Logistics Center (SM/ALC/MMET) learned of the use of acoustic emission monitoring for the detection of active corrosion. The original research into this application was performed by Rettig and Felsen [1] of Lockheed Aircraft, which has licensed Acoustic Emission Technology Corp. (AETC, Sacramento, CA.) to market equipment for this application. The AETC Model 201 Signal Processor System was procured in March 1975 and immediate work was initiated to solve inspection problems on the F-111 vertical and horizontal stabilizers.

Several vertical and horizontal stabilizer leading edge assemblies on F-111 aircraft have separated during supersonic flight in recent years. An extensive investigation was pursued by SM/ALC Service Engineering (MME) and General Dynamics to determine the cause of these failures. On the vertical stabilizer it was discovered that manufacturing defects (wormholes) in the adhesive-bonded leading edge were allowing water penetration into the honeycomb assembly (aluminum skins, phenolic core). It was shown that this condition leads to a degradation of the bond (~50% loss) between the phenolic core and the epoxy adhesive bonding the skin to the core. The characteristic appearance of this defective bond when skin and core are separated was dubbed "slick-off". A similar problem was diagnosed on the horizontal stabilizers, and an additional water entry problem from poor field repairs was recognized. The combination of weakened bonding/corrosion and high internal water vapor pressure arising from aerodynamic heating at supersonic velocities results in skin/core separation and eventual failure by dynamic flutter.

The Detection System

The AETC Model 201 Signal Processor is schematically outlined in Figure 1. The principal of operation is based upon the detection of sound or stress-wave signals in a select frequency range created by a material undergoing some physical or mechanical transformation. The sensor consists of piezoelectric crystal (PZT-5) with a resonant frequency of 175 KHZ. The preamplifier conditions, filters (125-250 KHZ bandpass), and amplifies (60 db fixed gain) the voltage signal from the sensor. The main 201 unit (postamplifier) provides up to 40 db of additional gain, giving the system a total gain of 100 db (10^5X). If the final amplified signal exceeds the threshold value of one volt, the event indicator (LED) is tripped for 50 milliseconds, giving a visible light emission. Other outputs available on the postamplifier are the amplified acoustic emission signal, the r.m.s. signal level intensity, the counter and the ramp generator. The digital counter stores the number of "ringdown" counts exceeding the threshold value and resets at user-selected values of 10^3, 10^4 or 10^5 total counts. The ramp generator is used to drive the X-axis of an X-Y plotter in the recording of r.m.s. and/or total count functions.

Corrosion Detection

Corrosion detection has not been a well-known application for acousti emission, although stress-corrosion cracking phenomena has been monitored by other workers [2] at relatively low gain levels (60-80 db). Dettig and Felsen [1] of Lockheed found that galvanic corrosion process could be monitored as well.

Figure 2 shows a portion of an F-106 elevon (aluminum, 1 3/4" max. co depth) we used in initial corrosion detection studies. A small charg of 10% KOH solution was injected into the core and acoustic emission counts were monitored at two inches from the source using different gain levels. Figure 3 shows clearly that at this detection distance gain levels below 90 db would be ineffective. Other studies have shown that even with the sensor directly over the corrosion source, almost no emission activity is recorded below 80 db gain. The sensor couplant does not seem to have much influence on this detection level. Figure 4 shows how the signal attenuation varies with distance from the corrosion source at 100 db gain. Actual inspection results on corroded honeycomb panels have confirmed the 2-3 inch detection limit. This does not imply that corrosion occurring in honeycomb depths greater than 3 inches would not be detectable. Corrosion has been successfully monitored on the F-111 horizontal stabilizer in eight inch honeycomb with 3/8" skin.

The source of emissions from pure corrosion activity is much debated, but the most plausible source is the nucleation of hydrogen gas bubbles from solution. Hydrogen is produced by cathodic reduction in all natural corrosion processes of aluminum alloys. We have readily monitored emission activity from a heated honeycomb panel injected with hydrogen peroxide, which results in oxygen bubble formation. Our experiments with controlling the hydrogen bubble size from corrosion of aluminum by reactive KOH solutions shows a definite relation between the bubble size and detection capability with acoustic emission. It is not disputed that expansion, rubbing, and breakage of corrosion products may contribute to emission activity, but the lack of activity from dormant (dried out) corroded areas does not tend to confirm this.

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Corrosion activity in aluminum can be monitored at room temperature, but in order to facilitate rapid hand scanning procedures it is usually desirable to heat the part or inspection surface to around 140-180°F (hot to the touch) to increase the corrosion rate. The corrosion rate roughly doubles for every 10°F rise in temperature, giving rise to equivalently higher acoustic emission rates.

Two methods of heating are currently used in our procedures. The first employs a hot air gun to heat the inspection area, after which the sensor is placed on the test location and the activity is monitored. Normally 15 seconds or less is required to establish the presence or absence of active corrosion at a test location. Where steady-state heating of a large area is required, infra-red or heat lamps are used at 6-12 inches from the inspection surface and monitoring takes place with the heat actively applied.

Depot procedures we have developed indicate that hand-held sensor monitoring and observing the event indicator light is adequate for most corrosion inspection applications. An operator can be trained in a relatively short time to hold the sensor steady enough not to cause emission activity by hand movements. The standard presently used is one data event per second for 15 seconds or longer minimum to indicate corrosion activity. Inspection intervals are from two to six inches, depending on the part configuration and the degree of mapping desired. Figure 5 demonstrates the manual technique currently used.

Figures 6, 7, 8 illustrate typical successes encountered in corrosion detection on the F-111 horizontal stabilizer using hand scan acoustic emission techniques. The ability to map even lightly corroded areas is clearly indicated. Acoustic emission has replaced costly and less effective X-ray and ultrasonic techniques in this application with direct savings of over 75% in inspection costs. Additional benefits accrue in more certain corrosion detection and mapping, which facilitates more rapid repair of defective stabilizers, and reduced interruption of other maintenance activity on the aircraft. Applications on a number of other honeycomb panels on the F-111 will be developed in the near future, as well as on other aircraft systems with similar problems.

Detection of Moisture-Degraded Adhesive Bonding

The detection of degraded epoxy adhesive bonding on the F-111 vertical stabilizer leading edge was serendipity. Initial studies were designed to detect corrosion in the aluminum skin where water entry had occurred, and a heat lamp was used to accelerate emissions. Figure 9 shows the vertical stabilizer leading edge with a typical acoustic emission scanning pattern. Figure 10 shows that on the first stabilizer inspected no significant emission activity was recorded until 3 1/2 feet down the front edge. Figure 11 shows the relative acoustic activity for the entire leading edge of the same assembly. The areas of maximum acoustic activity corresponded to areas with X-ray indications of standing water in the phenolic core, which were confirmed when the skin was removed.

A strange phenomenon occurred in the most heavily affected ("slick-off") areas of the panel that was not characteristic of corrosion activity. As the heat source was turned off, the emission rate rapidly increased (see Figure 12) for a few minutes before beginning a slow decline. It is presently concluded that the principal cause of these emissions is disbonding activity which has been accelerated by differential thermal stresses. The cooling cycle apparently places more tensile loading on the adhesive bond to the core walls, which is the weakest bonding mode. Further confirmation of this theory is displayed in Figure 13, which compared to Figure 3 shows a lower gain threshold necessary for monitoring this activity as compared to pure corrosion.

A hand scan acoustic emission technique using a hot air gun for local heating was developed, and excellent success has been recorded in detecting and mapping moisture-degraded-bond areas. Figure 14 and 15 show water-affected bond areas as marked by acoustic emission (dark outline) before and after skin removal. X-ray indications of moisture (light outlines marked "wet") did not reveal the true extent of water intrusion, as the arrows on Figure 15 indicate. Figure 16 shows another "slick-off" area detected easily with acoustic emission that was missed by X-ray. In subsequent studies, moisture affected areas the size of a finger have been detected. This is a significant improvement over the X-ray, eddysonic, and resonance ultrasonic procedures previously used, which it is now estimated may have missed detection of 25% or more of defective areas. In addition, the acoustic emission inspection of a complete vertical leading edge takes only 20 minutes if no defects are present, and up to an hour if defective areas must be mapped. Scanning is done at six inch intervals and mapping at three inch inspection intervals. This compares with 14 hours of inspection time, plus X-ray film cost, for the previous methods.

Other bonding weaknesses, such as poor skin-to-adhesive bonding can also respond to acoustic emission monitoring, depending on the severity of the stress gradient created by heating. Normally these areas suffer irreversible damage on the first couple of heating cycles and emission activity drops off to very low levels on successive cycles. Moisture-degraded bond areas respond vigorously on every heating (160-180°F) and cooling cycle. A sample F-111 vertical leading edge panel injected with water has responded continually to a hundred or more heating cycles over a three-month period. Well-bonded areas often do not emit at all using current heating techniques, and the same criteria of one event indication per second for longer than 15 seconds is used in this procedure to identify defective areas.

Advantages and Limitations

The monitored frequency range of 125-250 KH_z has proven to be the most advantageous in a maintenance environment. It is above the range of most mechanical noise and yet at the lower ultrasonic range where signal attenuation is not severe. Experiments with 375 KH_z and 750 KH_z peak response sensors show successive decline in both detection distance and received signal amplitude. The AETC Model 210 system has been used in noisy shop environments without mechanical noise interference problems. However, line electrical noise interference has been encountered on occasion when operating with high gains (greater than 90 db) from a poorly grounded 110 volt AC outlet. Future equipment developed for maintenance applications will probably have a dc-battery option and improved line filters to eliminate this problem.

An additional feature that enhances operator confidence is the addition of an audio converter unit that converts and amplifies signals to the audible range. The intensity and characteristic signature of emissions gives the operator a better sense of the source and cause of emission activity, and allows him to differentiate emission intensity levels above where the event indicator has saturated.

The basic simplicity of the detection system and techniques is a strong point for acoustic emission. No external calibration or standards are required to set up operation. On the other hand it is recognized that no two instrument/sensor combinations give exactly the same gain characteristics, and degradation of system or sensor performance with age should be considered. It is planned to acquire a broad-band ringing device that will check the entire system sensitivity and verify that some minimum sensitivity criterion is being met.

Conclusions

Acoustic emission is proving to be an important and reliable tool in the detection of active corrosion on weapons systems managed at Sacramento Air Logistics Center. The ability to detect corrosion activity and repair it before serious damage is done promises to strongly impact the inspection and maintenance philosophy of all military and commercial activities to whom corrosion has posed a problem. Additionally the ability of acoustic emission to detect moisture-degraded adhesive bonding could become an important NDT method for checking the integrity of epoxy-matrix composite structures on aircraft.

References:

1 Rettig, T. W., and Felsen, M. J., "Acoustic Emission Method for Monitoring Corrosion Reactions", NACE Journal, March 1974.

2 Hartbower, C. E.; Reuter, W. G.; Morais, C. F.; and Crimmins, P.P., "Acoustic Emission for the Detection of Weld and Stress-Corrosion Cracking", Acoustic Emission, ASTM STP 505, American Society for Testing Materials, 1972, pp. 187-221.

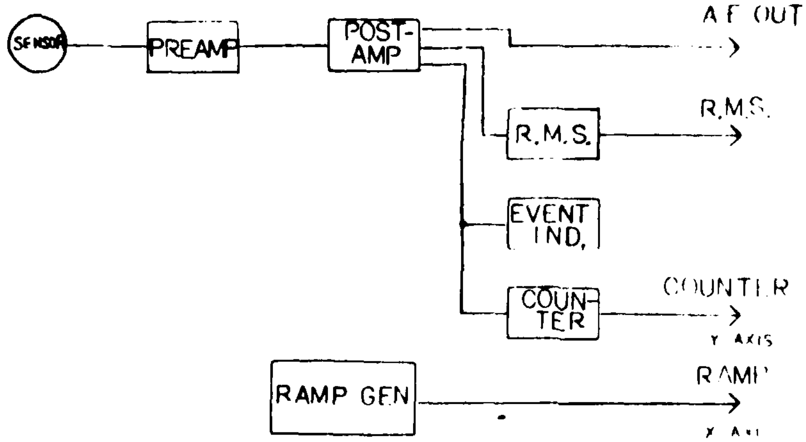


Figure 1. Simplified Block Diagram, AETC Model 201 Signal Processor.

Figure 2. F-106 elevon aluminum honeycomb panel used in initial corrosion studies. Circle marks corrosion source.

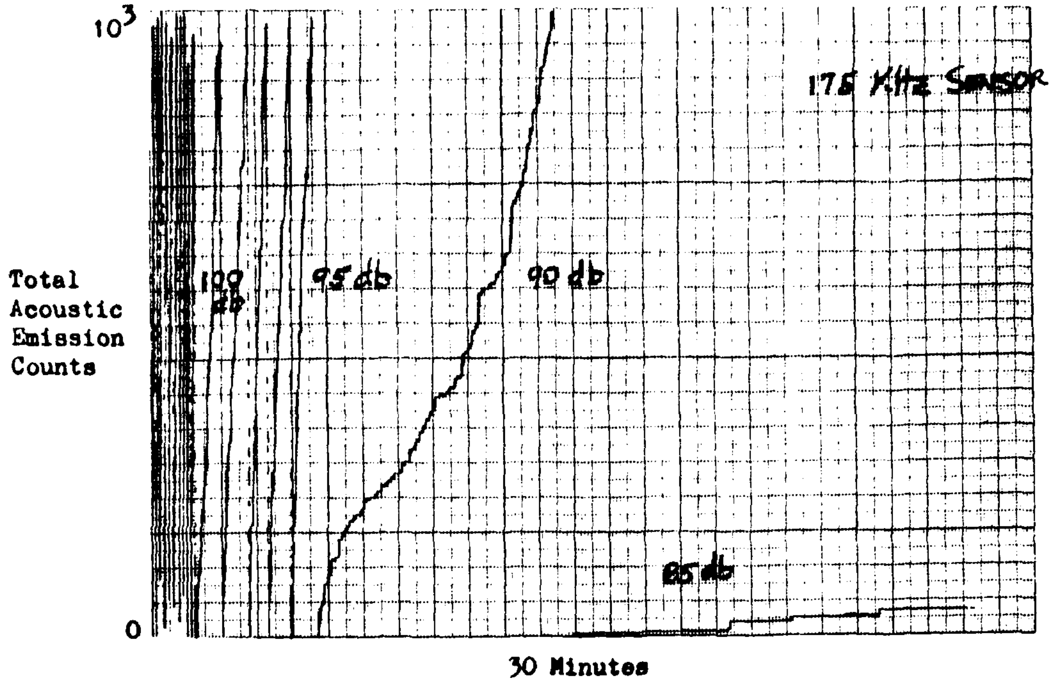


Figure 3. Acoustic Emission Counts vs. Time at different gains. F-106 honeycomb panel; sensor 2" from 10% KOH corrosion source.

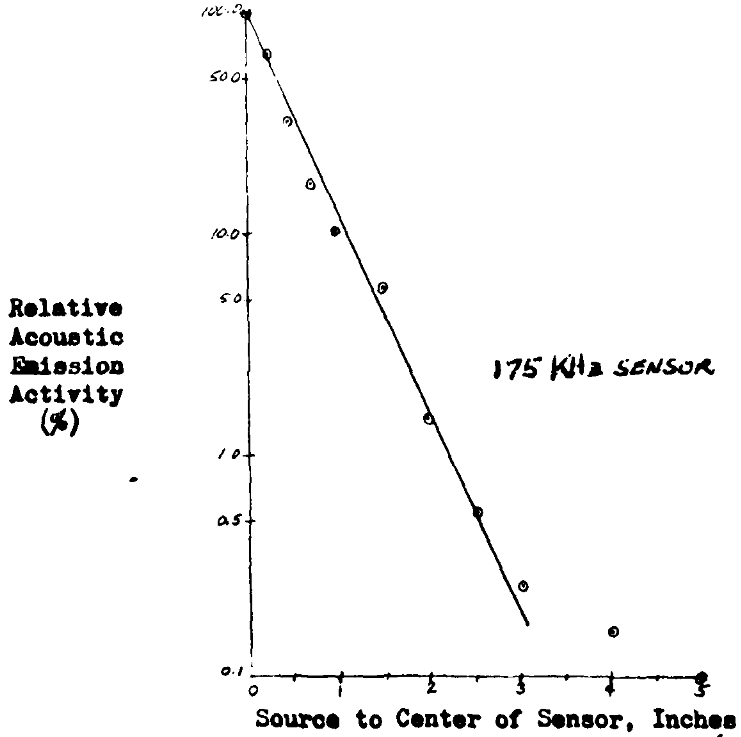


Figure 4. Attenuation of corrosion emissions with distance from 10% KOH source in F-106 aluminum honeycomb panel. 100 db gain.

Figure 5. Acoustic emission hand scan technique using AETC Model 201 Signal Processor and hot air gun heating.

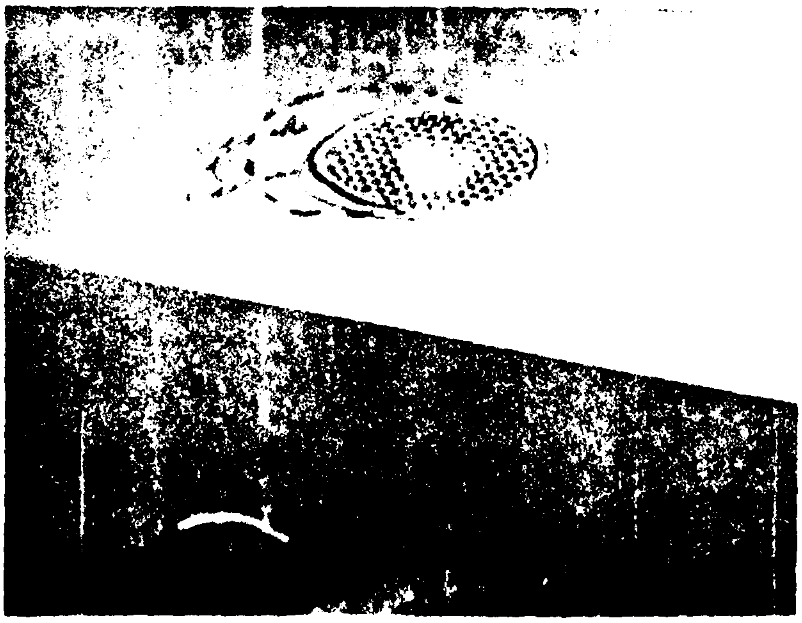
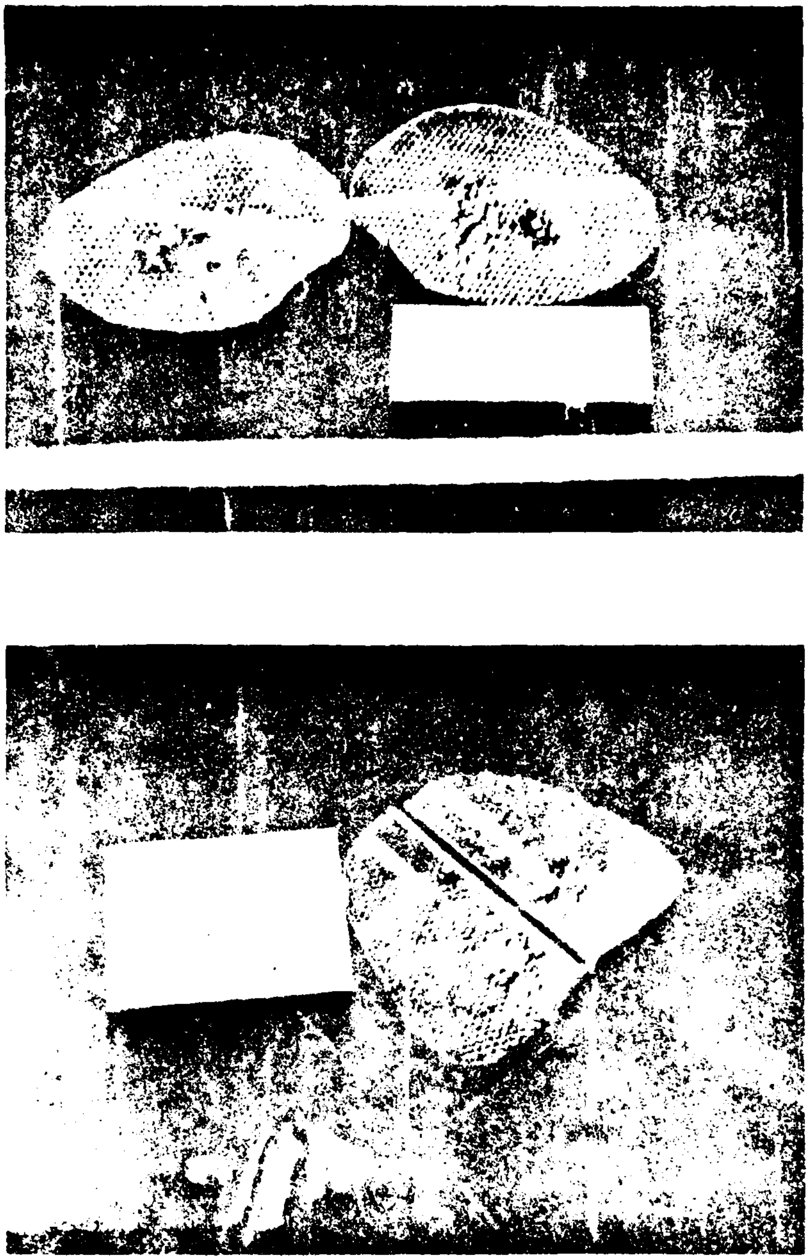


Figure 6. Corrosion in aluminum honeycomb core discovered with acoustic emission. F-111 horizontal stabilizer, bad skin repair.



Figures 7 & 8. Corrosion in aluminum honeycomb mapped by acoustic emmission. F-111 horizontal stabilizer.

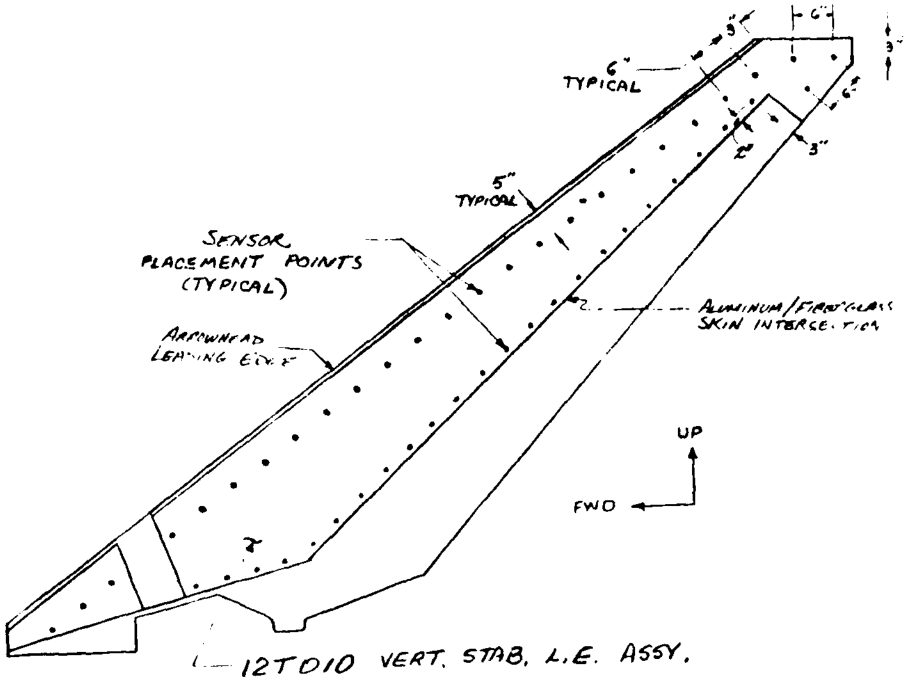


Figure 9. F-111 vertical stabilizer leading edge acoustic emission scanning pattern

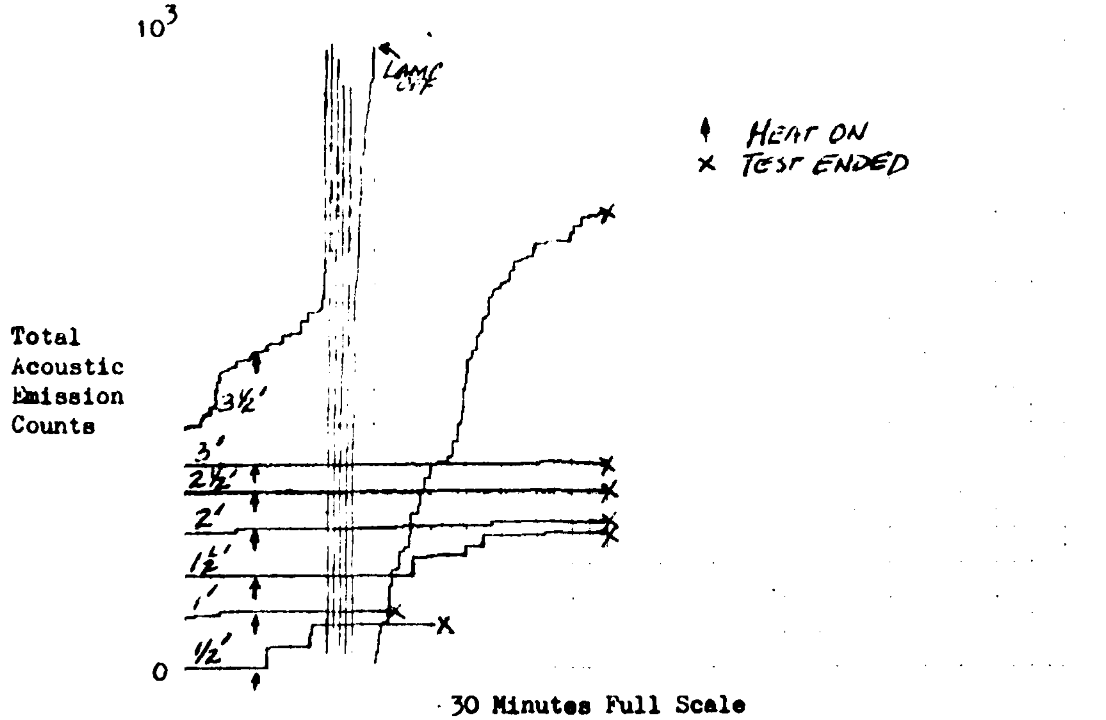


Figure 10. F-111 vertical stabilizer leading edge (A/C 68-005), recorded acoustic emmission activity with heating (160°F) at 6" intervals from top of leading edge. 100 db, 175 KHz sensor.

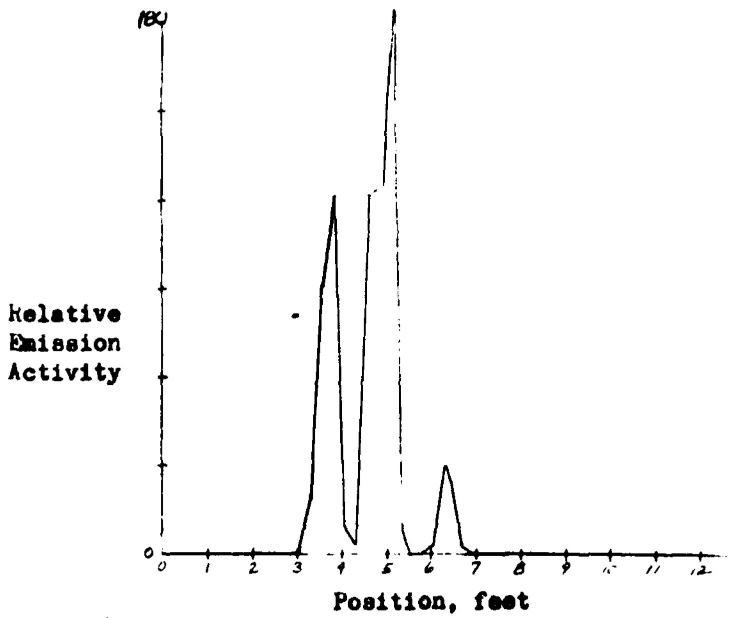


Figure 11. A/C 68-005 vertical leading edge relative acoustic activity with position (see Fig. 10).

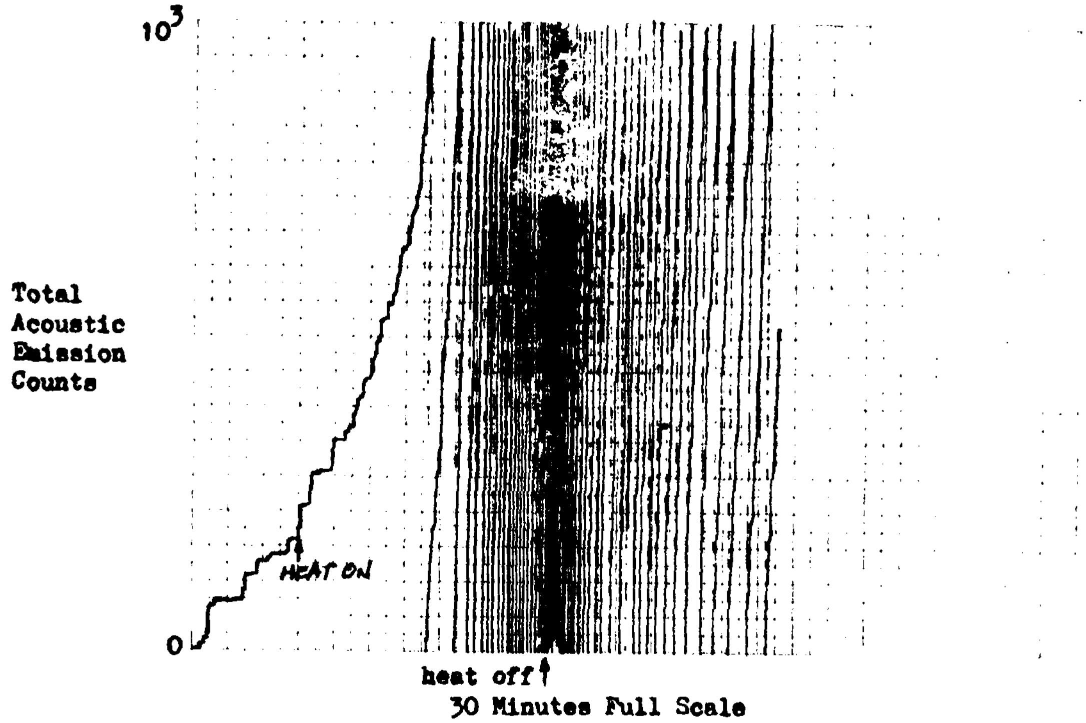


Figure 12. Acoustic emission response to heating of a moisture-degraded bond area on vertical stabilizer leading edge. Temporary increase in activity on cooling cycle is evident.

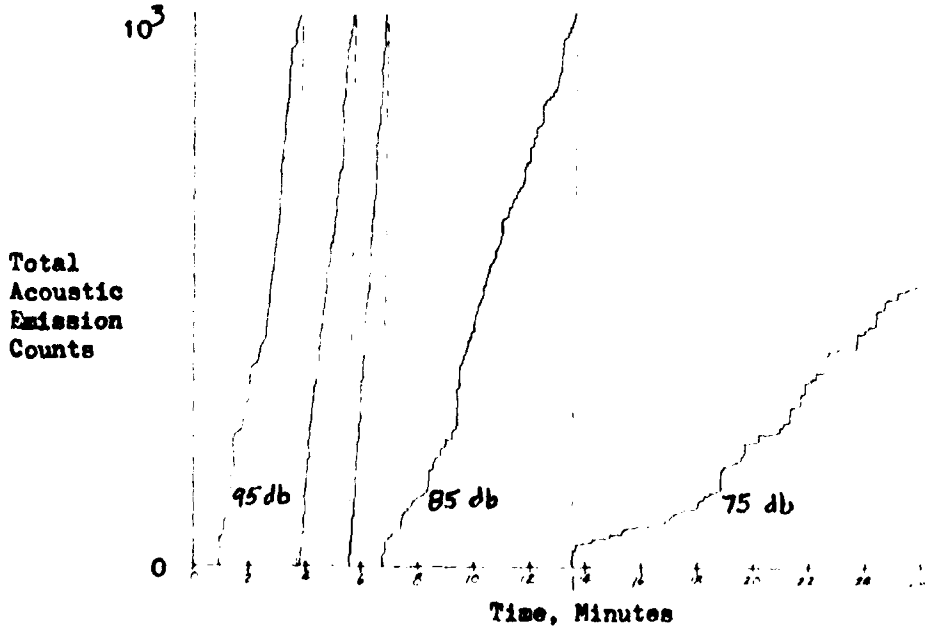


Figure 13. Vertical stabilizer emission activity (disbonding) recorded at different gains.

Figures 14 & 15. F-111 Vertical stabilizer leading edge inspected by acoustic emission (dark outline) and X-ray (light outlines marked "wet"), before and after skin removal. Arrows denote area missed by X-ray.

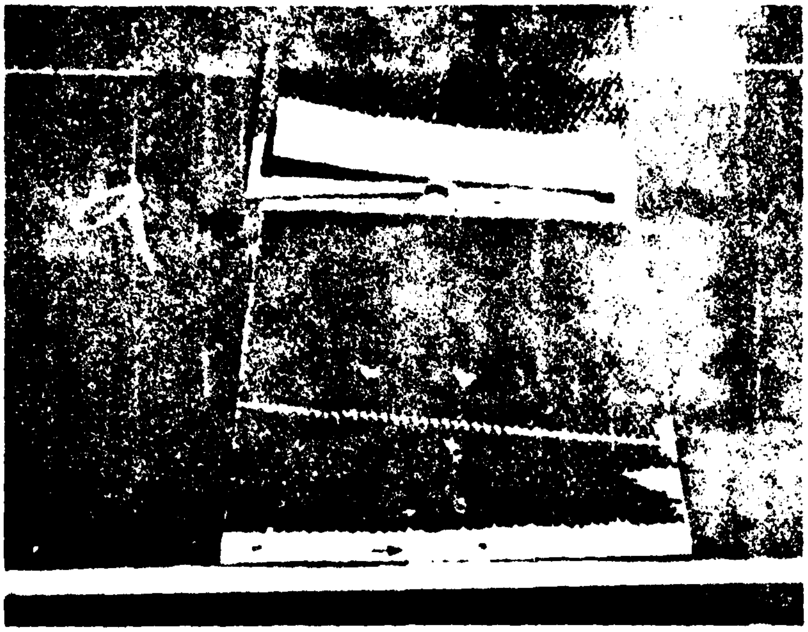


Figure 16. Moisture-degraded (slick-off) area mapped with acoustic emission on F-111 vertical stabilizer leading edge. Area was missed in previous X-ray inspection due to lack of standing water in honeycomb. Arrow denotes wormholes in arrowhead bond which allowed water entry.

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